Ultra-Stable Large Telescope Research and Analysis (ULTRA)

ExEP Technology Colloquium

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Outline

- Study Objectives and Scope
- Study Approach – Error Budgeting
- Key Analysis Areas and Trades
- Technology Gaps and Roadmap

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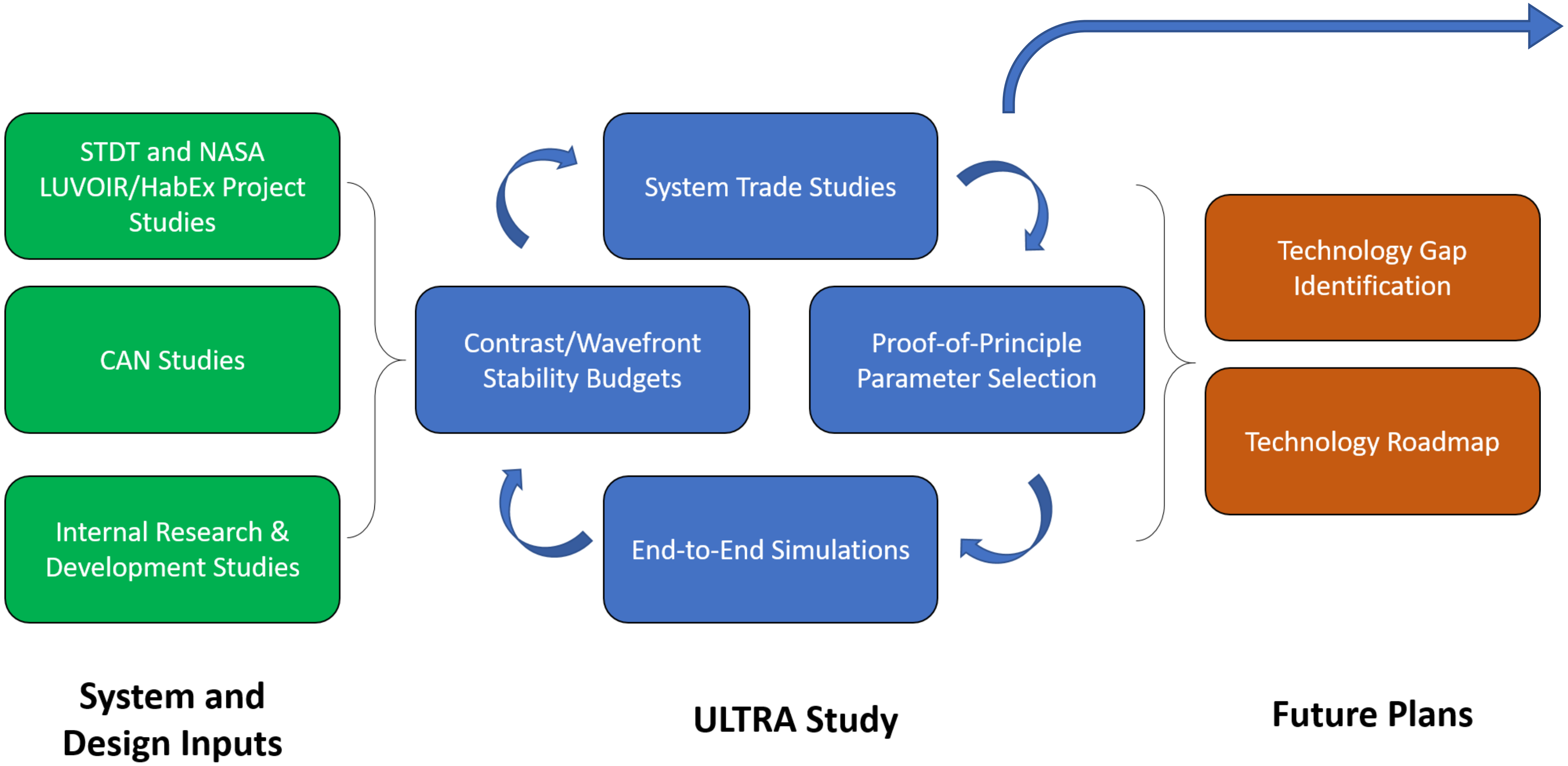
Objectives

- The ULTRA Industry Team was formed to support the maturation of key technologies for large, ultra-stable telescopes

- In 2018, the team received an award through ROSES (Element D.15) to perform a one year design and modeling study for > 10 m class segmented aperture telescopes.
- The key objectives of the effort were:
  1. Develop technical details of time domain aspect of stability, controls and coronagraph observations
  2. Develop thorough list of on-board and off-board disturbances important at picometer levels
  3. Develop trade space for technologies/architectures
  4. Develop technology gaps/roadmaps based on stability budgets

Study Scope



STDT and NASA LUVOIR/HabEx Project Studies

CAN Studies

Internal Research & Development Studies

System Trade Studies

Contrast/Wavefront Stability Budgets

Proof-of-Principle Parameter Selection

End-to-End Simulations

Technology Gap Identification

Technology Roadmap

System and Design Inputs

ULTRA Study

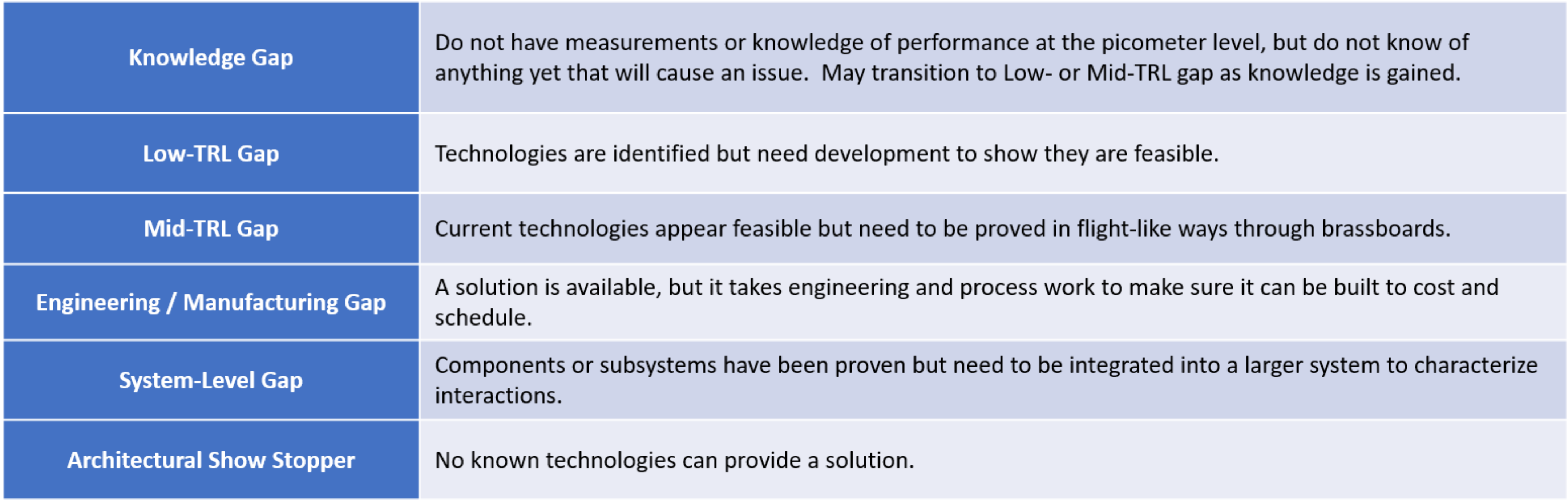
Future Plans

<u>Analysis Areas</u>

Perturbations (Induced/Environmental)
Structural Materials
Structure Joining and Latching
Mirror Materials
Mirror Mounting
Segment Sensing and Control
Beam Walk/LOS
System Control Methodology
Coronagraph Performance

Technology Gap Classification

- Different gap types require different approaches to close



Knowledge Gap	Do not have measurements or knowledge of performance at the picometer level, but do not know of anything yet that will cause an issue. May transition to Low- or Mid-TRL gap as knowledge is gained.
Low-TRL Gap	Technologies are identified but need development to show they are feasible.
Mid-TRL Gap	Current technologies appear feasible but need to be proved in flight-like ways through brassboards.
Engineering / Manufacturing Gap	A solution is available, but it takes engineering and process work to make sure it can be built to cost and schedule.
System-Level Gap	Components or subsystems have been proven but need to be integrated into a larger system to characterize interactions.
Architectural Show Stopper	No known technologies can provide a solution.

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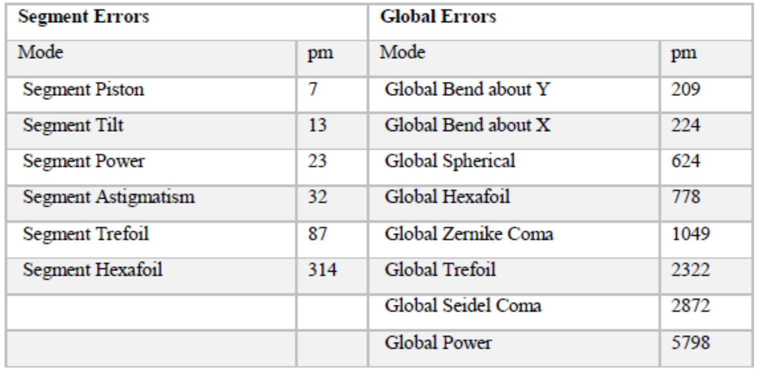
Contrast Stability Budget

- Budgeting for contrast stability is a complex exercise
  - Depends on coronagraph design, observing scenario, angular separation of planet-star, temporal and spatial scale of perturbations/control system, telescope performance, etc.
  - <u>Not all aberrations are created equal</u>

SPATIAL DOMAIN

Allowable spatial perturbations to maintain 1^-10 contrast

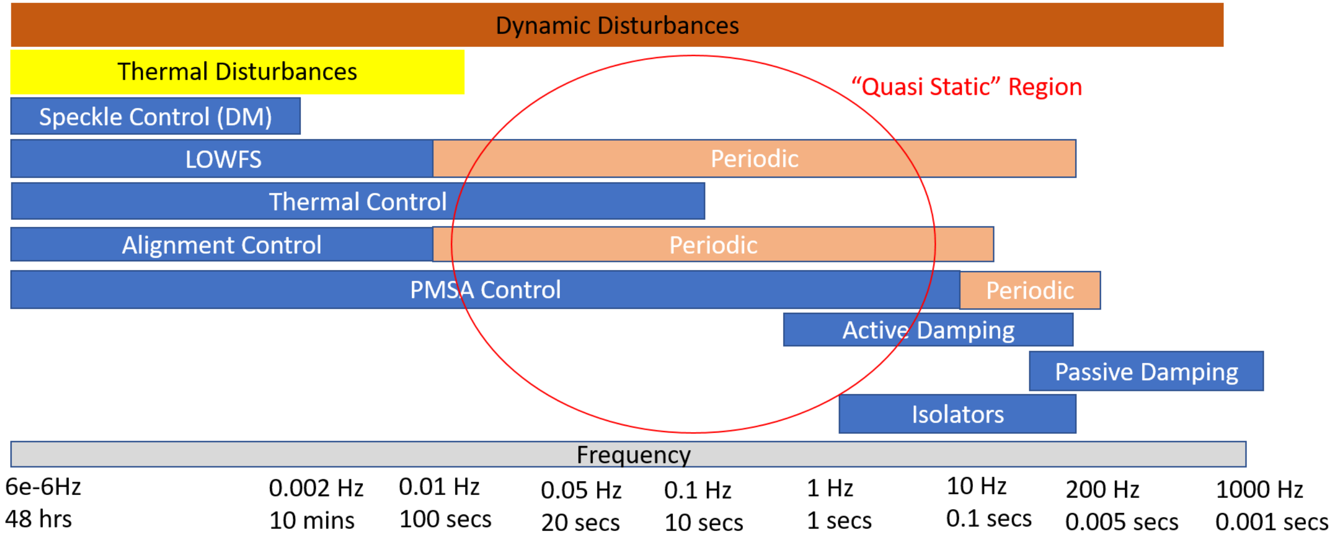


Segment Errors		Global Errors	
Mode	pm	Mode	pm
Segment Piston	7	Global Bend about Y	209
Segment Tilt	13	Global Bend about X	224
Segment Power	23	Global Spherical	624
Segment Astigmatism	32	Global Hexafoil	778
Segment Trefoil	87	Global Zernike Coma	1049
Segment Hexafoil	314	Global Trefoil	2322
		Global Seidel Coma	2872
		Global Power	5798

Nemati et al., “The effects of space telescope primary mirror segment errors on coronagraph instrument performance,” Proc. SPIE 10398 (2017).

TEMPORAL DOMAIN

Expected disturbances and notional control systems



Coronagraph Sets Top Level Allocations

- Coronagraph sensitivity is a function of spatial, temporal perturbations
  - “10 picometers per 10 minutes” isn’t enough
- Defined initial allocations in 15 “bins”
  - 3 Spatial frequency bins set by mirror segmentation (global, segment rigid, segment figure)
  - 5 Temporal frequency bins set by control systems (HOWFS, LOWFS, laser metrology, edge sensors, uncontrolled)

	Low Spatial Frequency (low)	Mid Spatial Frequency (mid)	High Spatial Frequency (hi)
Low Temporal Frequency 1 (LF1)	50 pm/10 hours (SF) 100 nm/10 min (CFWS)	[1,1.7,1.7] pm/10 hours (PTT – SF) [0.8,4,5] nm/10 min (PTT – CWFS)	0.04 pm/10 hours (SF) 0.6 pm/10 min (CWFS)
Low Temporal Frequency 2 (LF2)	100 nm/10 min	[0.8,4,5] nm/10 min (PTT)	0.6 pm/10 min (CWFS)
Low Temporal Frequency 3 (LF3)	100 nm/10 min	PSD < [24,35,38] pm RMS (PTT)	PSD < 10 pm RMS
Mid Temporal Frequency (MF)	PSD < 100 pm RMS	PSD < [24,35,38] pm RMS (PTT)	PSD < 10 pm RMS
High Temporal Frequency (HF)	PSD < 100 pm RMS	PSD < [24,35,38] pm RMS (PTT)	PSD < 10 pm RMS

APLC, Raw contrast 10^-10, planet to star ratio 10^11, mv = 5 host star

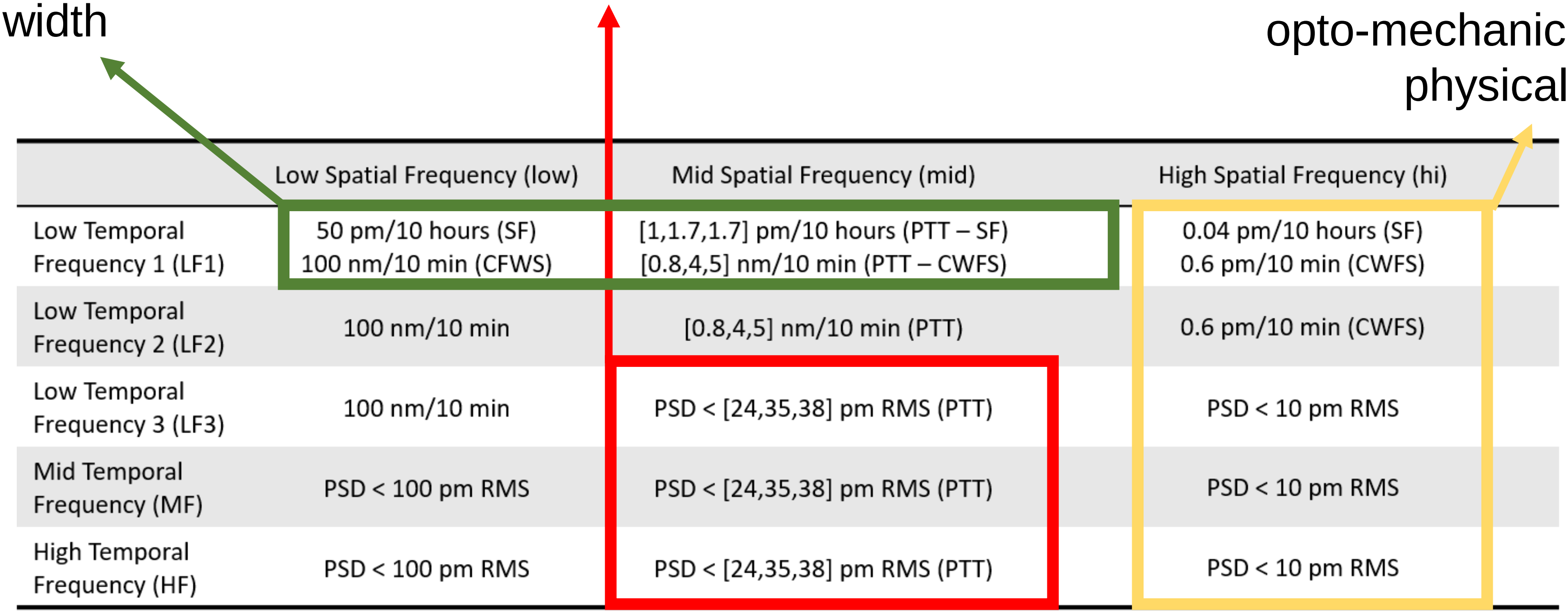
Coronagraph Sets Top Level Allocations

Segment Piston, Tip, and Tilt (PTT) have tight allocations above 0.02 Hz (~2 min) "Quasi-static" segment errors are going to be the most difficult part of the stability problem

LOWFS/HOWFS provide significant relief below their operating bandwidth

High spatial frequency numbers need more refinement – generated using conservative assumptions (e.g. pure sinusoidal phases that aren't opto-mechanically realizable in a physical telescope)

*direction from science community on definition of contrast and whether it is a maximum value, average over the dark hole area, etc. is needed



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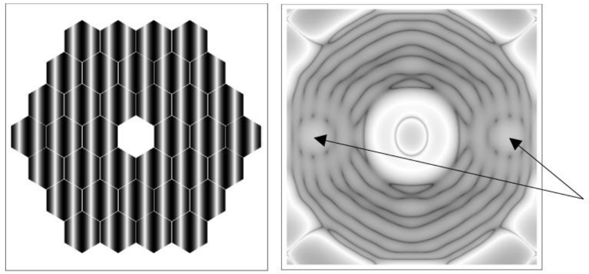
PSD Approach to Budgets

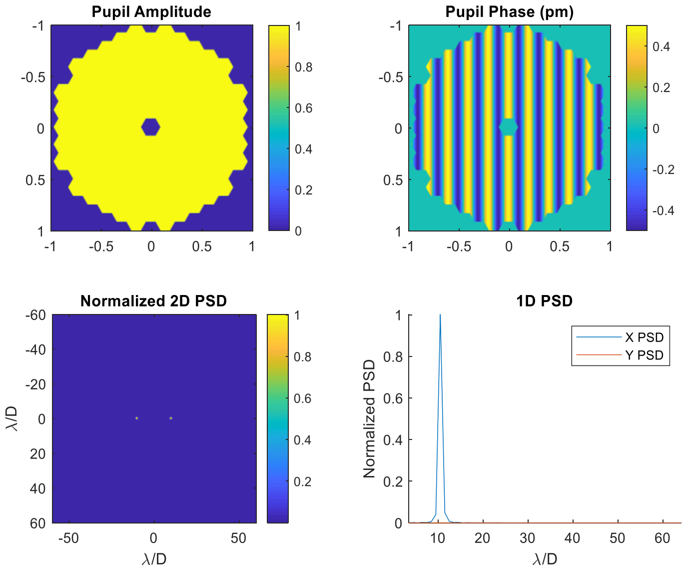
- Two types of WFE with the same RMS can put energy into different locations in the coronagraph focal plane
  - <u>As long as they don't spatially overlap, they don't work together to degrade contrast</u>
  - RSS'ing the WFE in a traditional branching structure may be overly conservative

- Use PSD to calculate energy distribution in the dark hole from errors on the PM (or other optics)
  - Use coronagraph simulation to calculate energy increase in dark hole that degrades contrast by 10^-10, use as a normalization factor (e.g. phase sinusoid)
  - Assumes coronagraph effect is stationary – not quite right, but suitable for initial allocations
  - Final check: end-to-end simulation



Peaks from sine wave phase error

Sine Phase Error creates distinct peaks in dark hole



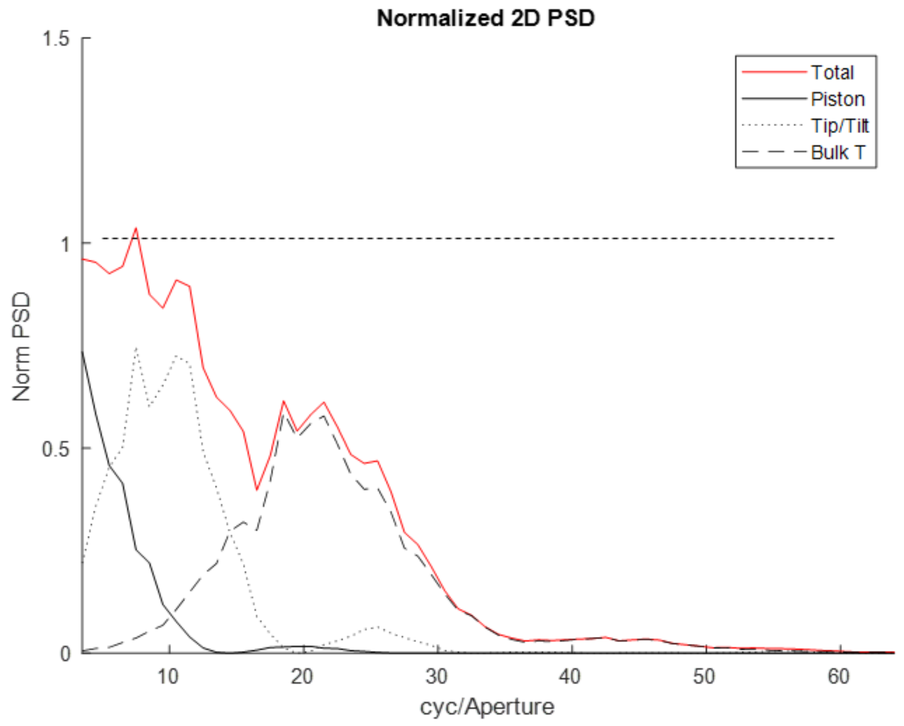
Peak energy used to calculate normalization factor (max allowable energy at any location)

Example PSD Budget

- The most sensitive spatial terms in the error budget are segment level piston, tip and tilt
  - Create a PSD “sensitivity” for each term
  - Scale such that the PSD sum is below the requirement

- This method provides some relief to the error budget
  - In an RSS WFE approach, each term would get 58% of the allocation (1/sqrt(3))
  - In the PSD approach, the peaks are shifted, so each term gets ~80% of the allocation

- Normalization factor will also scale based on temporal nature of perturbation



Sample Monte Carlo PSD-based budget for spatial terms:
Segment level piston
Segment level tip/tilt
Bulk temperature change of segment (trefoil)

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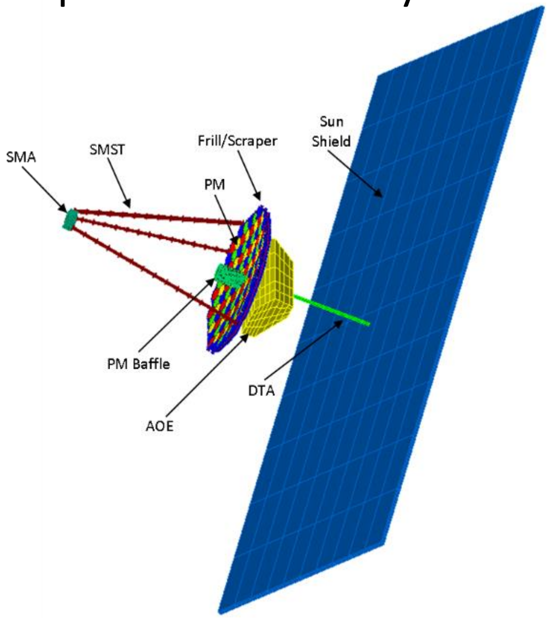
Baseline Design

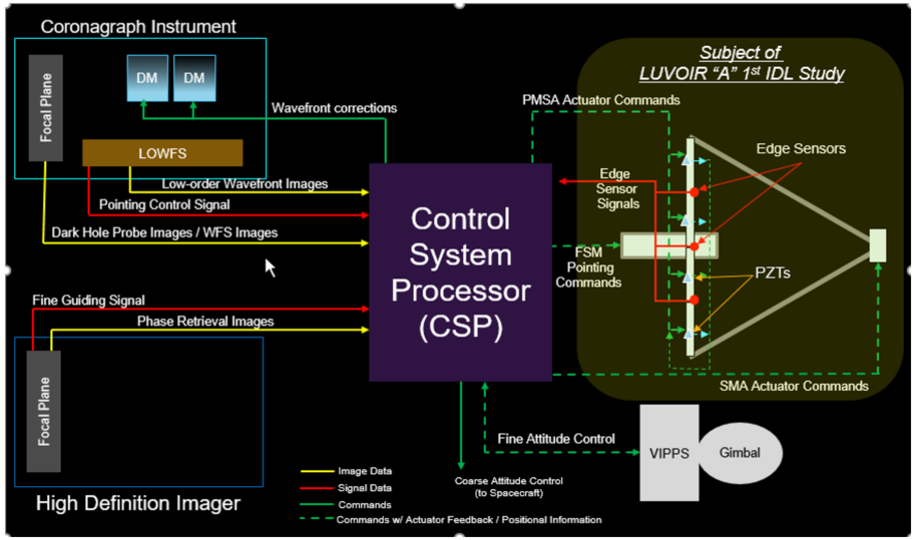
- LUVOIR Architecture A was used as the baseline when a specific system was needed
  - Tried to generalize/parametrize analysis where possible
- On the following slides, the hardest problems/areas of concern are highlighted

Optomechanical Layout



LUVOIR Architecture “A”
Harris Corp., LUOVIR STDT

Control Architecture



Lee Feinberg; Matthew Bolcar; Scott Knight; David Redding,” Ultra-stable segmented telescope sensing and control architecture.” Proc. SPIE Volume 10398, (2017).

Expected Disturbances

Sources Considered:

	Environmentally Induced	**System Induced**
Classical Sources	• Thermal distortion from solar flux (function of telescope orientation/slew)	• Thermal distortion from on-board sources • Moisture Desorption • S/C Dynamics: CMGs, propellant slosh • Payload Dynamics: hinges, latches, mechanisms
New Sources	• Gravitational Forces (Sun/Earth/Moon) • Charging – Coulomb Forces (electrostatics) and Lorentz Forces (electrodynamics) • Radiation Induced Compaction • Micrometeoroid impacts (dynamics)	• Gravitational Forces (Self-interaction) • Inertial Forces from station keeping

Knowledge Gap

Potential Concerns:

- Coulomb Forces
  - Approaching nm level over 1 year
  - Static figure concern over mission lifetime
  - High spatial frequency – may fall outside the dark hole
- Micrometeoroid Impacts
  - May result in > 1 pm displacement of PMSAs during CG observation
  - Very conservative assumptions used – need to study energy transfer in more detail

Beam Walk/LOS

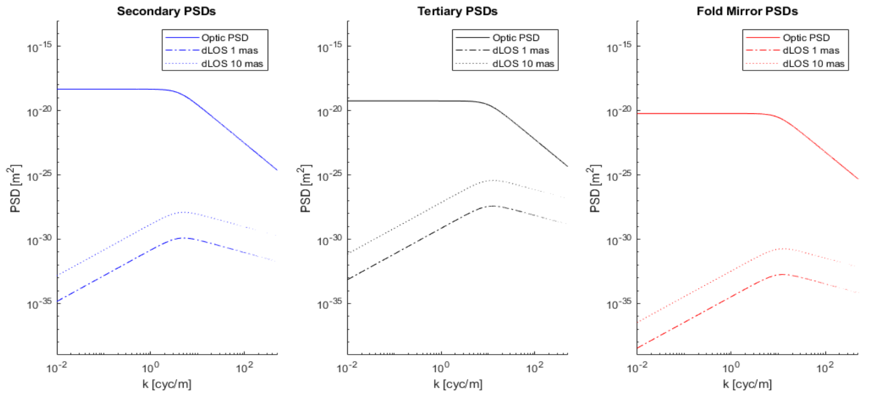
- Beam walk is caused by misaligning an optical element or changing the LOS
- Has three main impacts on system WFE:
  1. Shear on the optical surface will expose the beam to a different part of the ideal surface shape, which will add a slightly different wavefront error.
  2. Shear on the optical surface will expose the beam to spatially varying manufacturing residuals, which will add a slightly different wavefront error.
  3. Shear on a deformable mirror will cause the wavefront correction produced by the DM to no longer line up properly.

(Deferred to E2E simulation)

Driver for allowable optic misalignment (control with WFE budget)

Driver for allowable LOS change (< 1 mas LOS control – needs low disturbance S/C or isolation/damping)

Low TRL Gap



PSD Analysis for Beam Walk, Manufacturing Residual

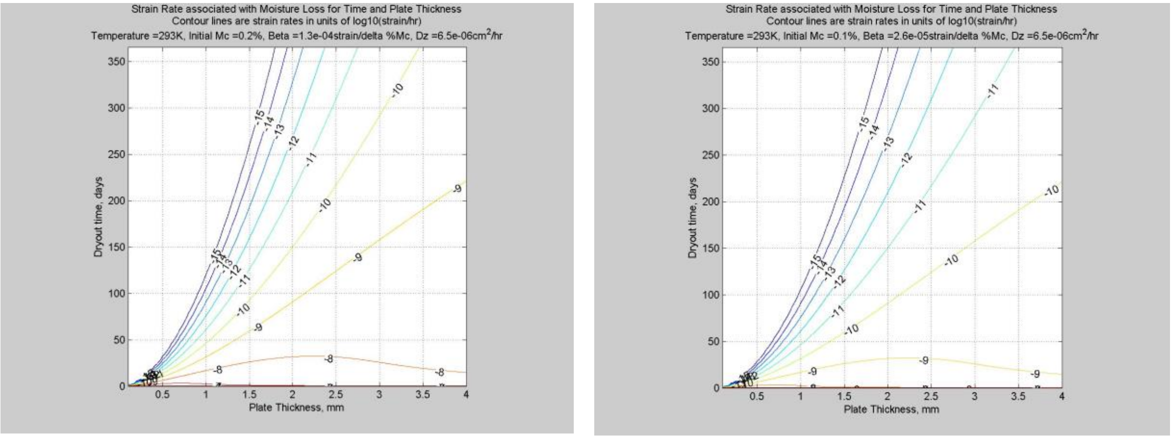
Stable Structures

- Evaluated performance of SOTA composite structures
  - Dimensional change from thermal gradients, moisture desorption – Need improved knowledge of CTE, CME to meet current budgets efficiently (screen materials at production rates)

    Engineering Gap
  - Improvements needed in thermal performance of fittings/adhesives/latches

    Mid TRL Gap
  - More work needed to characterize effect of micro dynamics in large structure

    Knowledge Gap
- Key Trades:
  - CME: Bakeout, operating temp
  - Temperature control spatial uniformity



Moisture Desorption Analysis for Baseline vs. 50% reduced CME

Frequency Band	Source	PM Global Alignment Expectations						PM Figure (PMSA) Alignment Expectations					
		V1 (nm)	V2 (nm)	V3 (nm)	Clocking rV1	Tilt rV2	Tilt rV3	V1 (nm)	V2 (nm)	V3 (nm)	Clocking rV1	Tilt rV2	Tilt rV3
LF1	Allocation	2E+03	8E+03	8E+03	3E+05	1E+03	1E+03	9E+02	7E+02	2E+02	9E+05	4E+02	4E+02
	CS Joint Fitting CTE	4E+03	6E+01	1E+03	1E+02	2E+03	6E+01	1E+04	7E+04	8E+04	3E+03	2E+04	1E+04
MF	Allocation	5E-02	2E-01	2E-01	7E+00	3E-02	3E-02	2E-01	2E+00	5E-02	2E+02	9E-02	9E-02
	CS Joint Fitting CTE	1E-01	3E-03	7E-03	1E-03	3E-02	8E-03	2E-01	7E-02	9E-02	4E-02	1E-01	1E-01

Frequency Band	Source	PM Global Alignment Expectations						PM Figure (PMSA) Alignment Expectations					
		V1 (nm)	V2 (nm)	V3 (nm)	Clocking rV1	Tilt rV2	Tilt rV3	V1 (nm)	V2 (nm)	V3 (nm)	Clocking rV1	Tilt rV2	Tilt rV3
LF1	Allocation	2E+03	8E+03	8E+03	3E+05	1E+03	1E+03	9E+02	7E+02	2E+02	9E+05	4E+02	4E+02
	Adhesive CTE Influence	2E+03	1E+02	2E+03	1E+02	1E+03	1E+02	1E+04	2E+04	2E+04	6E+03	2E+04	2E+04
MF	Allocation	5E-02	2E-01	2E-01	7E+00	3E-02	3E-02	2E-01	2E+00	5E-02	2E+02	9E-02	9E-02
	Adhesive CTE Influence	4E-02	2E-03	3E-03	4E-03	8E-03	1E-03	3E-02	6E-02	7E-02	1E-02	4E-02	7E-02

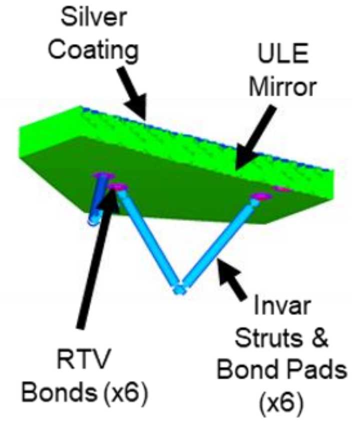
Optic misalignment due to Fitting/Adhesive CTE
(yellow indicates significant work needed to meet budgets)

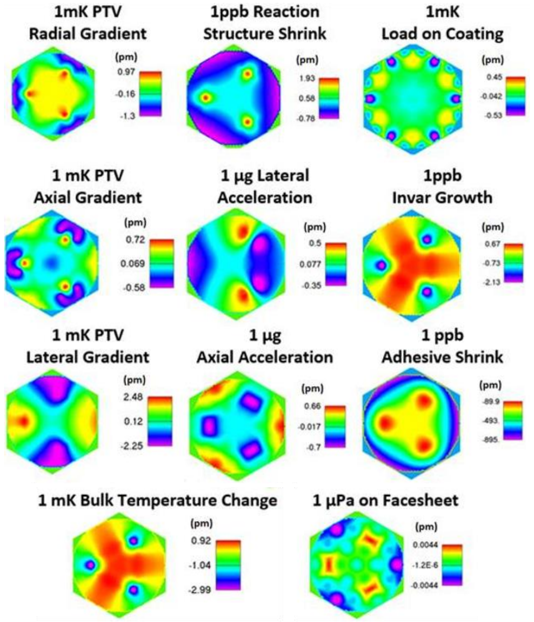
Stable Mirrors

- Evaluated performance of SOTA ULE Mirrors
  - Surface figure deformation sensitivities
  - Thermal time constants
  - Slew settling
  - Allowable temperature changes
  - Dynamic load limits
- Key Trades:
  - Mirror Material (ULE, Zerodur, SiC)
  - Mirror Mass Budgets
  - Mirror Mounting Approaches (bond pads, struts, etc. to reduce thermal impacts)

Mid TRL Gap

Opto-mechanical model, surface deformation sensitivities





Thermal Analysis

Tolerable mK change and rate of chage over spec duration		Acceptable Bulk Change in PMSA Temperature		Acceptable Bulk Change in Mirror Substrate		Axial Gradient Temp change in PMSA		Lateral Gradient Temp change in PMSA	
Alloc	Duration	mK Change	mK/Hour Rate	mK Change	mK/Hour Rate	mK Change	mK/Hour Rate	mK Change	mK/Hour Rate
LF1	86400 s	114.5 mK	3.4 mK/h	80.4 mK	2.4 mK/h	165.5 mK	6.9 mK/h	351.9 mK	10.4 mK/h
LF2	1000 s	4.5 mK	11.4 mK/h	3.1 mK	8.0 mK/h	1.5 mK	5.3 mK/h	13.7 mK	34.9 mK/h
LF3	100 s	4.5 mK	113.6 mK/h	3.1 mK	79.8 mK/h	1.5 mK	53.0 mK/h	13.7 mK	>500 mK/h
MF	1 s	0.064 mK	>500 mK/h	0.045 mK	>500 mK/h	0.040 mK	>500 mK/h	0.195 mK	>500 mK/h
HF	0.1 s	0.064 mK	>500 mK/h	0.045 mK	>500 mK/h	0.003 mK	>500 mK/h	0.034 mK	>500 mK/h

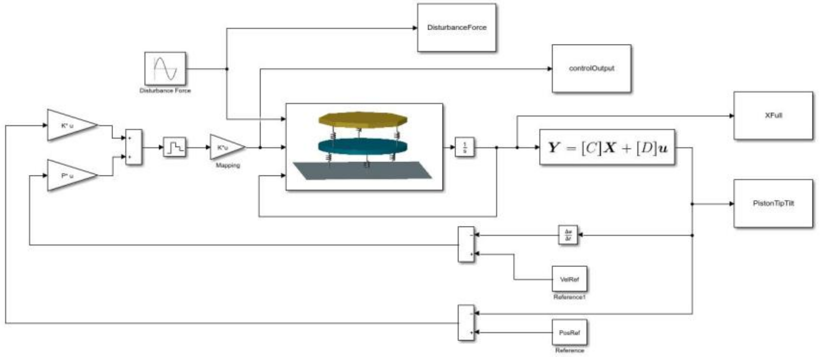
Active Sensing and Control

- System Control Methodology
  - Building up simulation to model perturbations, active sensing and control system, disturbance rejection controller
- Thermal Sensing and Control
  - Assumed 1 mK for this study
  - Baseline sensitivity demonstrated, need to apply to large, complex opto-mech system
- Key Trades:
  - Sensing approach (edge sensor, segment level LOWFS, external laser guide star)
  - Actuator approach (PZT, Voice Coil)
  - Local vs. Distributed Control

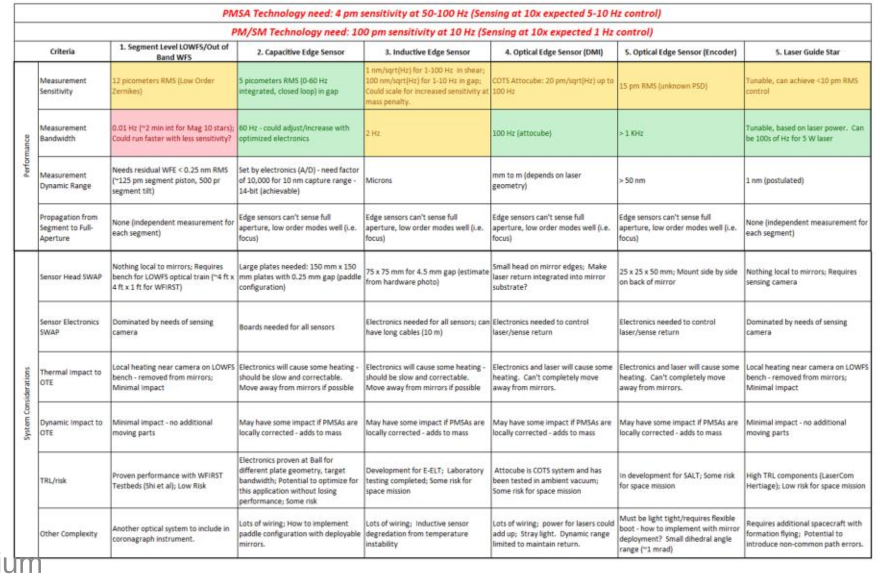
Mid TRL Gap

Low TRL Gap

Control Model



Sensing Trade Study Matrix



PMSA Technology need: 4 pm sensitivity at 50-100 Hz (Sensing at 10x expected 5-10 Hz control)

PM/SM Technology need: 100 pm sensitivity at 10 Hz (Sensing at 10x expected 1 Hz control)

Criteria		1. Segment Level LOWFS/Out of Band WFS	2. Capacitive Edge Sensor	3. Inductive Edge Sensor	4. Optical Edge Sensor (DMI)	5. Optical Edge Sensor (Encoder)	5. Laser Guide Star
Performance	Measurement Sensitivity	12 picometers RMS (Low Order Zernikes)	5 picometers RMS (0-60 Hz integrated, closed loop) in gap	1 nm/sqrt(Hz) for 1-100 Hz in shear; 100 nm/sqrt(Hz) for 1-10 Hz in gap; Could scale for increased sensitivity at mass penalty.	COTS Attocube: 20 pm/sqrt(Hz) up to 100 Hz	15 pm RMS (unknown PSD)	Tunable, can achieve <10 pm RMS control
	Measurement Bandwidth	0.01 Hz (~2 min int for Mag 10 stars); Could run faster with less sensitivity?	60 Hz - could adjust/increase with optimized electronics	2 Hz	100 Hz (attocube)	> 1 KHz	Tunable, based on laser power. Can be 100s of Hz for 5 W laser
	Measurement Dynamic Range	Needs residual WFE < 0.25 nm RMS (~125 pm segment piston, 500 pr segment tilt)	Set by electronics (A/D) - need factor of 10,000 for 10 nm capture range - 14-bit (achievable)	Microns	mm to m (depends on laser geometry)	> 50 nm	1 nm (postulated)
	Propagation from Segment to Full-Aperture	None (independent measurement for each segment)	Edge sensors can't sense full aperture, low order modes well (i.e. focus)	Edge sensors can't sense full aperture, low order modes well (i.e. focus)	Edge sensors can't sense full aperture, low order modes well (i.e. focus)	Edge sensors can't sense full aperture, low order modes well (i.e. focus)	None (independent measurement for each segment)
System Considerations	Sensor Head SWAP	Nothing local to mirrors; Requires bench for LOWFS optical train (~4 ft x 4 ft x 1 ft for WFIRST)	Large plates needed: 150 mm x 150 mm plates with 0.25 mm gap (paddle configuration)	75 x 75 mm for 4.5 mm gap (estimate from hardware photo)	Small head on mirror edges; Make laser return integrated into mirror substrate?	25 x 25 x 50 mm; Mount side by side on back of mirror	Nothing local to mirrors; Requires sensing camera
	Sensor Electronics SWAP	Dominated by needs of sensing camera	Boards needed for all sensors	Electronics needed for all sensors; can have long cables (10 m)	Electronics needed to control laser/sense return	Electronics needed to control laser/sense return	Dominated by needs of sensing camera
	Thermal Impact to OTE	Local heating near camera on LOWFS bench - removed from mirrors; Minimal Impact	Electronics will cause some heating - should be slow and correctable. Move away from mirrors if possible	Electronics will cause some heating - should be slow and correctable. Move away from mirrors if possible	Electronics and laser will cause some heating. Can't completely move away from mirrors.	Electronics and laser will cause some heating. Can't completely move away from mirrors.	Local heating near camera on LOWFS bench - removed from mirrors; Minimal Impact
	Dynamic Impact to OTE	Minimal impact - no additional moving parts	May have some impact if PMSAs are locally corrected - adds to mass	May have some impact if PMSAs are locally corrected - adds to mass	May have some impact if PMSAs are locally corrected - adds to mass	May have some impact if PMSAs are locally corrected - adds to mass	Minimal impact - no additional moving parts
	TRL/risk	Proven performance with WFIRST Testbeds (Shi et al); Low Risk	Electronics proven at Ball for different plate geometry, target bandwidth; Potential to optimize for this application without losing performance; Some risk	Development for E-ELT; Laboratory testing completed; Some risk for space mission	Attocube is COTS system and has been tested in ambient vacuum; Some risk for space mission	In development for SALT; Some risk for space mission	High TRL components (LaserCom Hertiage); Low risk for space mission
	Other Complexity	Another optical system to include in coronagraph instrument.	Lots of wiring; How to implement paddle configuration with deployable mirrors.	Lots of wiring; Inductive sensor degradation from temperature instability	Lots of wiring; power for lasers could add up; Stray light. Dynamic range limited to maintain return.	Must be light tight/requires flexible boot - how to implement with mirror deployment? Small dihedral angle range (~1 mrad)	Requires additional spacecraft with formation flying; Potential to introduce non-common path errors.

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Mid-TRL Gap	Current technologies appear feasible but need to be proved in flight-like ways through brassboards.
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Technology Gap List

Area	Active Sensing & Control				Low Disturbance			Structures			Mirrors and Mirror Mounting					
Technology	Segment Dynamic Sensing & Control	Laser Metrology	System Control Methodology	Thermal Sensing & Control	LOS Stability	Payload Isolation	Low Disturbance Mechanisms	Stable Composite Structures	Microdynamics	Stable Joining (Hinges/Latches)	Stable Mirrors	Mirror Mounting	PMSA Figure Actuation (if needed)	Coronagraph Design (LOWFS/HOWFS)	Infrastructure/ External Metrology	Path Forward for TRL Advancement
Current TRL	3	5	2	4	3	5	2	5	2	4	5	4	3	4/5	-	
Knowledge Gap	X		X	X	X		X		X	X		X	(X)			Analysis/ Measurements
Low-TRL Gap	**X**		**X**		**X**								(X)			**Component-Level Demo**
Mid-TRL Gap				**X**						**X**		**X**				**Analysis/ Subsystem Demo**
Engineering Gap		X				X		X			X				X	Analysis
System-Level Gap	X				X			X			X					System/ Subsystem Demos
Showstopper																Unknown

We did not identify any “show stoppers”

However, making this architecture work requires technology development in multiple areas (no “silver bullet”)

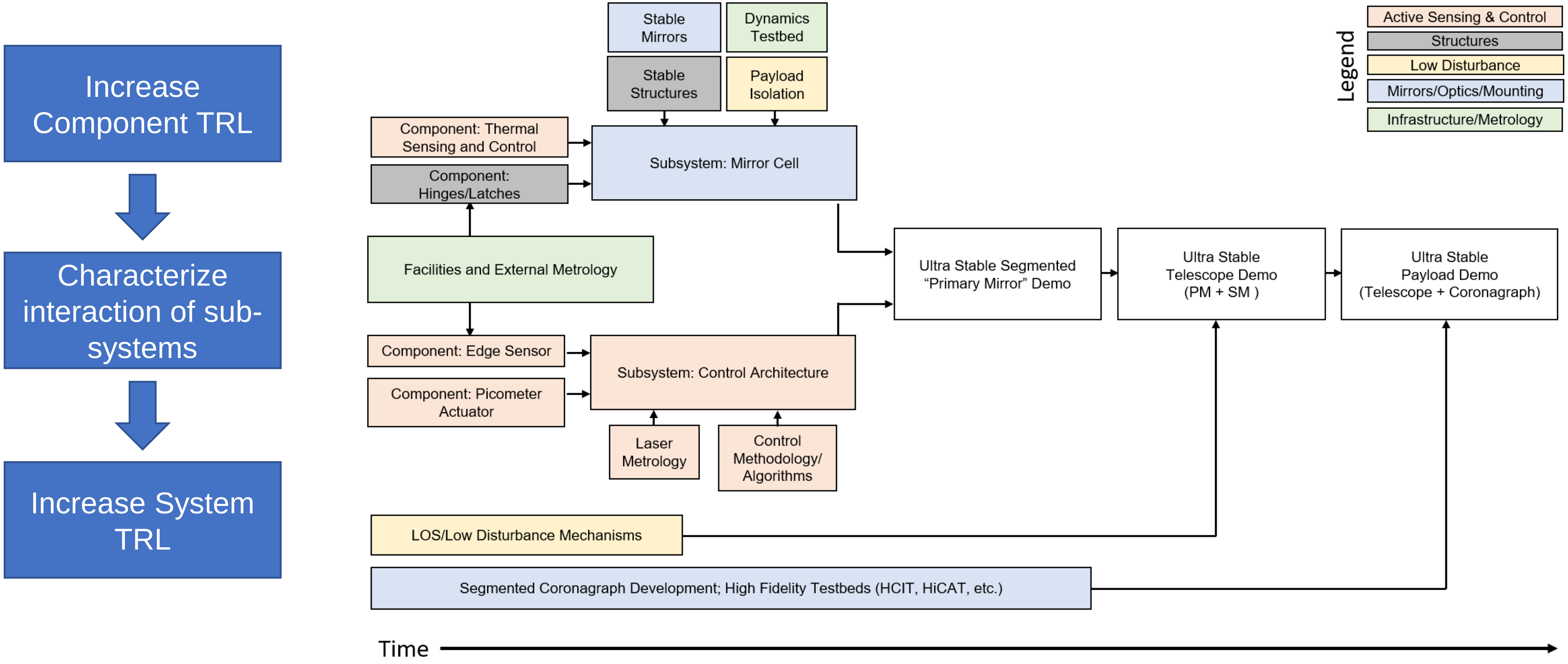
TRL Justification

- Most Low TRL gaps (2-3) are component technologies and have a proposed approach(es), but they have not been demonstrated at the picometer level and/or in a LUVOIR-like geometry
- Most knowledge/engineering gaps (3-5) can be solved with better manufacturing/metrology.
  - Knowledge gaps could transition to Low TRL gaps depending on results

Near-term priorities

- The Mid TRL gaps (4) need to be proven through subsystem interactions.
- Everything falls into the system-level gap – no one has put all these pieces together and demonstrated stability to picometers

Technology Roadmap



Increase Component TRL

Characterize interaction of sub-systems

Increase System TRL

Stable Mirrors

Dynamics Testbed

Stable Structures

Payload Isolation

Component: Thermal Sensing and Control

Component: Hinges/Latches

Subsystem: Mirror Cell

Facilities and External Metrology

Component: Edge Sensor

Component: Picometer Actuator

Subsystem: Control Architecture

Laser Metrology

Control Methodology/ Algorithms

Ultra Stable Segmented “Primary Mirror” Demo

Ultra Stable Telescope Demo (PM + SM)

Ultra Stable Payload Demo (Telescope + Coronagraph)

LOS/Low Disturbance Mechanisms

Segmented Coronagraph Development; High Fidelity Testbeds (HCIT, HiCAT, etc.)

Time

Legend

- Active Sensing & Control
- Structures
- Low Disturbance
- Mirrors/Optics/Mounting
- Infrastructure/Metrology

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